Proceedings – 23rd Annual Conference – IEEE/EMBS Oct.25-28, 2001, Istanbul, TURKEY

THE DESIGN OF MAMMARY GLAND TUMOR PHANTOM FOR MICORWAVE RADIOMETERS

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Abstract-**Microwave Radiometry is the spectral measurement technique of resolving electromagnetic radiation of all matters which temperature is above absolute zero. This technique utilized the electromagnetic noise field generated by a thermal volume similar to a mechanism existing in biological tissues. One particular application of Microwave Radiometry is for analyzing temperature differentials of inside of human body to detect and diagnose some crucial pathologic conditions. For general evaluation of radiometer, we propose a new mammary gland tumor phantom simulating heat diffusion propagated by tissues around tumors. Theoretical researches of human tumors revealed the fact that temperature distribution of tissues around tumor formed a gaussian statistics. To comply with this physiological property, we built a tumor imitator composed of two parts, pseudo-tumor and thermo-anomaly, and observed the temperature distribution of tumor imitator inside a phantom. Our experimental results showed that the thermal properties of tumor imitator well agreed with heat transfer properties of a real tumor.**

Keywords **– Microwave radiometry, mammary gland tumor phantom.**

I. INTRODUCTION

The theory of ‘‘Black-body Radiation’’ implies that all matters at temperature above absolute zero emit electromagnetic radiation due to the motion of the charged particles of their atoms and molecules. The level of emission is a function of both frequency and temperature. Microwave Radiometry is a spectral measurement device for the electromagnetic radiation dissipated at frequency bands in the microwave region. Microwave radiometer utilizes the electromagnetic noise field generated by a thermal volume similar to heat transfer mechanism existing in biological tissues. One particular medical application of the radiometer is for analyzing temperature differentials inside human body to detect and diagnose crucial pathologic conditions.

During the last decade, many research groups demonstrated its possible usage of clinical application for early breast cancer diagnosis [1]-[4]. They introduced the prototypical radiometers based on the principle of ‘‘Dicke’’ radiometer [5]. Simultaneously, their own biological phantom models were also proposed to evaluate their prototypes of radiometers. Their phantoms were actually tumor imitators placed into the medium. The temperature of tumor imitator differed from its surrounding medium one by a certain amount of degree. The phantom was supposed to be allowed to experimentally determining the following spatial resolutions of a radiometer:

- Minimum spatial size of a tumor imitator ($\Delta_{x,y}$),
- Maximum detectable depth of a tumor imitator ($L_{\max}$),
- Minimum detectable temperature difference ΔT between a tumor imitator and its surrounding biologic tissue one.

But most of their phantoms did not provide such meaningful measures. For example, Plancot et al. [2] suggested a biological phantom model. This model comprised a main container filled with water of T_0 temperature. A substantially long cylindrical object of a smaller diameter D (2^{nd} container) was vertically placed in the basic container. It was filled with water of $T_0 + \Delta T$ temperature. The bottom of the 2^{nd} container was spaced apart from the bottom of the main container by a variable distance Z. The antenna-applicator of two radiometers with the central receiving frequencies 1.5 and 3 GHz were contacted with the bottom side of main container through a radio-transparent window. The ratio $\Delta T_R / \Delta T$ (ΔT_R : radiometer readings) with respect to Z for the various D values, the visibility with respect to D for the various Z values were sought. The temperature resolution of the radiometer was about 0.1 °C.

But this phantom model cannot be utilized as a mammary gland tumor. Water and solutions on its base may be used as some biologic tissue substitutes. But due to the discrepancy of their physical structures, the heat transfer mechanism between the contents of the main container and the 2^{nd} one is actually different from a heat transfer mechanism between a real mammary gland tumor and it’s surrounding the tissue. Besides, this phantom model lacks constructional properties and other important aspect, which would allow judging how and what error water temperature values T_0 and $T_0 + \Delta T$ are kept in the main and the 2^{nd} container. Without this judgment it is impossible to have the confidence on their claimed data and application for a real biologic tissue with a carcinogenic tumor.

Mizushina et al. [3]-[4] also described a medical radio-thermometer system to retrieve a depth temperature profile inside biologic tissue by measuring the brightness temperature using multi-frequency radio-thermometer. Their phantom model comprised a water bath that was equivalent to a muscle agar phantom. The water temperature was maintained about 45 °C. The bottom side of phantom was uniformly heated by bath water of 45 °C and the top one of phantom was cooled with circulating the distilled water of 22 °C. The distilled water was pumped through a plastic box with water layer depth of 10 mm. Thermocouples for direct temperature measurements were placed in a plastic box at the different height levels. A contact typed waveguide antenna attached to a multi-frequency radiometer was achieved through a plastic box of 10 mm thickness. But such a phantom did not allow forming a local thermal anomaly. Besides the substitution of mammary gland tissue (especially

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
25OCT2001	N/A	-

Title and Subtitle The Design of Mammary Gland Tumor Phantom for Micorwave Radiometers	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) M Application Project Team Samsung Advanced Institute of Technology Yong-In, Korea	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es) US Army Research, Development & Standardization Group (UK) PSC 802 Box 15 FPO AE 0949-1500	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)

Distribution/Availability Statement
Approved for public release, distribution unlimited

Supplementary Notes
Papers from the 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, October 25-28, 2001, Istanbul, Turkey. See also ADM001351 for entire conference on cd-rom., The original document contains color images.

Abstract

Subject Terms

Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU

Number of Pages
4

of its upper layers) by a muscular equivalent tissue medium was not justified.

To overcome these lacks of generality in the previous phantom designs, we propose more generalized biological phantom scheme that truly imitates the mammary gland tumor.

II. MAMMARY GLAND TUMOR PHANTOM

The main problem of a phantom construction is non-adequacy of the heat transfer mechanism in liquid imitating media (e.q. distilled water or physiologic saline) and biologic tissues. The prevalence of the convection mechanism leads to a substantial difference in formation of a thermal anomaly area, which determines a radiative power received by radiometer.

Most phantoms for evaluating radiometer are composed of a bath with circulating physiologic saline solution. Our goal is to design and build a new conceptual phantom containing a medium imitating a biologic tissue after considering biological heat transfer mechanism. We constrct and evaluate 3 water vessels phantom to achieve our goals.

A. Physiological properties of the proposed phantom

Fig. 1 shows our proposed mammary gland tumor phantom configuration. The phantom is mainly imitating mammary gland tumor. But its concept can be easily extended to the other types of biological tissues. The main water bath is made of acryl plastic that is adiabatic and impermeable. Fluid contained in the main bath is forced to flow by an external circulator (HAKKE F6-B5, Germany). This circulator controls the temperature of the main bath with the constant level of T1. The circulation of the main bath is maintained at a slow speed. This ensures thermodynamic equilibrium between the fluid of the main bath and the tumor imitator. We use the distilled water as medium for the main water bath since its electromagnetic property in the certain frequency range is quite similar to fatty tissue [6].

B. Mammary Gland Tumor Imitator

A mammary gland tumor imitator is placed in the middle of main water bath. Between a radiometer and distilled water, the skin equivalent material (0.05mm thick polyethylene film) is inserted as a radio-frequency transparent window. The tumor imitator is composed of two parts; a glass tube which simulates a tumor itself, and polyurethane sponge which wraps up the glass tube. This sponge simulates heat diffusion effects generated by a real tumor. The distilled water is circulated through the glass tube using a water circulator (HAKKE F6-C25, Germany). The circulation rate inside the glass tube must be high to maintain the constant temperature value within ±0.05 °C accuracy level. Also, the flow rate must high enough to prohibit a glass tube from generating air bubbles. If the flow rate is slow, the air bubbles can be formed and these bubbles can greatly affect the measurement readings of radiometer. Fig. 2 illustrates two types of structures in mammary gland tumor imitators that are used in our experiments.

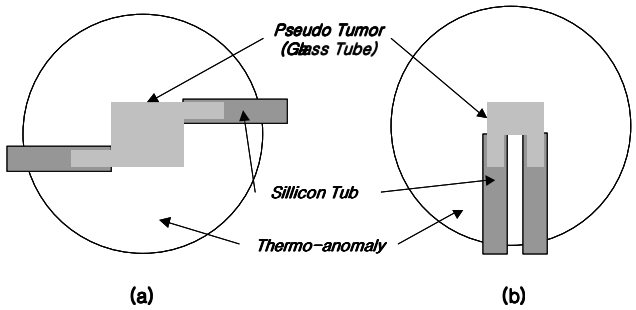


Fig. 2. Structure of mammary gland tumor imitator.
(a) Unidirectional (UD) model, (b) Countercurrent (CC) model

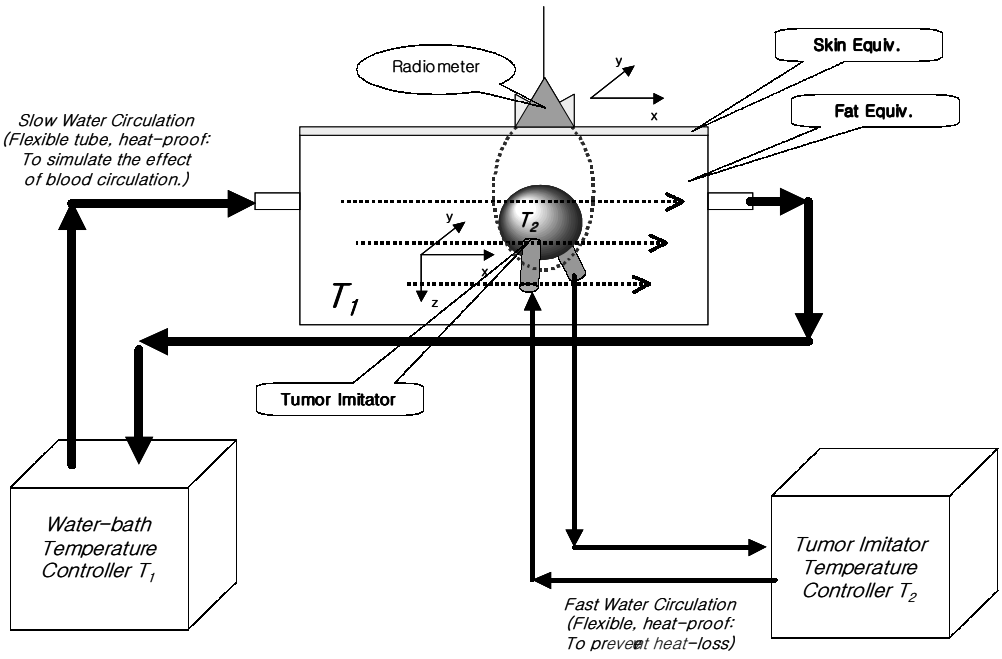


Fig. 1. Our proposed 3-water vessels mammary gland tumor phantom considering physiological properties.

C. Temperature distribution within living tissue and thermo-anomaly

The temperature of biological tissue is controlled by local blood circulation, metabolism, and heat exchange between surrounding tissue [7]. And it has been found that the blood circulation and the local metabolism heat generation are dominant effects that mainly affect the temperature of tumor. Changes in any of these parameters can induce variation of the temperature of tissue or tumor and reflect physiological state of the living organs in human body. The bioheat transfer equation [8] itself is an approximation to the heat transfer processes in the tissue. To predict the general characteristics of temperature distribution within the body, the bioheat transfer equation (1),

$$\nabla \cdot (k \nabla \cdot T_t) - \omega_b C_b (T_t - T_a) + q = \rho c \, \partial T_t / \partial t \qquad (1)$$

where k - intrinsic thermal conductivity ($W/m\cdot^0C$), T_t - local tissue average temperature (^0C), T_a - arterial blood temperature (^0C), ω_b - blood perfusion rate ($kg/m^3 \cdot s$), c_b - specific heat of blood ($J/kg\cdot^0C$), q - rate of volumetric heat generation in tissue (W/m^3), ρ - tissue density (kg/m^3), c - specific heat of tissue ($J/kg\cdot^0C$), was widely accepted and used to predict detailed local temperature distributions and thermal energy transport in living tissue. The four terms in (1) are intended to represent thermal energy diffusion, perfusion of solids by liquids, metabolic heat generation, and thermal energy storage, respectively.

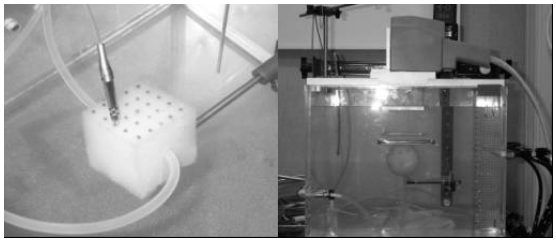
The fact that the blood perfusion greatly affects the thermal characteristics of living tissue is well known. From many vascular models of tissue [9], we choose two models; 1) unidirectional (UD) vessel configuration, 2) countercurrent (CC) vessel configuration. Fig.2 shows our proposed vascular models.

Also, thermal interaction of tissue with blood vessel should be considered. If there is no other medium between pseudo-tumor and distilled water in main bath, the convective heat flow would be a dominant factor affecting heat energy transfer and this phenomenon would not happen in living tissue, that is, the temperature gradient between pseudo-tumor and distilled-water medium becomes steep. To overcome the abrupt change of heat energy transfer rate, we use a porous material such as polyurethane sponge, because the anisotropic properties of porous material considerably modify the heat transfer rates from that expected under isotropic conditions [10].

III. EXPERIMENT RESULTS

To evaluate the adequacy of our proposed mammary gland tumor phantom model, we implement a phantom with 3-vessel configuration. Fig. 3 shows our experimental setups. Mammary gland tumor imitator is composed of a glass tube with 10 x 15 mm, radius 50mm volume. Thermo-anomaly, which is used to simulate the thermal diffusion around tumor, is made of polyurethane sponge. The radius of this medium is about 60 mm. To measure the temperature of thermo-anomaly, we used hypodermic syringe thermocouple sensor (OMEGA, USA) as shown in Fig. 4(a).

Fig. 3. Experimental setup of mammary gland tumor phantom



(a) (b)

Fig. 4. (a) Measuring the temperature distribution of thermo-anomaly, (b) radiometer measuring of mammary gland tumor imitator.

Fig. 5 shows the temperature profile of our experimental tumor imitator models. Solid line and one with mark '+' represent the temperature of unidirectional tumor model, parallel to fluid flow and perpendicular to fluid flow, respectively. Solid line with mark 'o' and one with mark '♦' represents the temperature of countercurrent tumor model. The temperature difference between pseudo-tumor and main water is 5°C. These results represent the adequacy of countercurrent tumor model. Although we used silicon tube for circulation of fluid in pseudo-tumor, the temperature distribution around tube does not diminished. It means that thermal flow inside the tube contributes to the measurement of radiometer that measure volume-averaged temperature. The temperature difference between perpendicular and parallel measurement is up to 0.7°C and this difference could affect greatly diagnostic decision.

Fig. 6 shows the effect of thermo-anomaly in tumor imitator. Solid lines with mark 'x' and '+' represent radiometer measurements without thermo-anomaly, parallel and perpendicular to fluid flow, respectively. Solid line and one with 'o' mark represents radiometer measurements with thermo-anomaly. Measurements with thermo-anomaly are performed when tumor-imitator is located at depth 3cm from the radio-transparent window with temperature difference of 7°C between pseudo-tumor and the main bath. But the measurements without thermo-anomaly are performed at depth 0.5cm with the same temperature difference. Fig. 6 also shows that tumor-imitator without thermo-anomaly is observed as scaled down. From these results, we can find the fact that our thermo-anomaly well simulate thermal energy diffusion and cause tumor imitator to be observed like a real tumor.

Fig. 7 shows the dependence of temperature difference on tumor imitator depth position. This experiments is performed when radiometer is located over the tumor imitator and without tumor imitator. Solid line represents the difference between consecutive measurements with the presence of tumor imitator and with the absence of one for the case of ΔT is 5°C. Line with mark 'o' represents the radiometer measurement difference for the case of ΔT is 7°C. From our experimental results, we can find the fact that as depth of tumor imitator increases, the level of radiometer measurement is decreased. As the temperature difference between pseudo-tumor and main water increases, the measured temperature difference is also increased. If we can assure of the linearity of a radiometer, we can infer the minimum detectable size of tumor with a radiometer.

IV. CONCLUSION

In this paper, we propose a new phantom design considering physiological properties of human body to evaluate and calibrate a microwave medical radiometer. The most important aspect of our phantom is design of imitating mammary gland tumor. Also, this proposed phantom model could be utilized in determining phantom performance parameters such as maximum detectable depth, and minimum detectable temperature difference. Further study on more reliable phantom construction can provide the concrete base of theory for microwave radiometry and its application to medical diagnosis.

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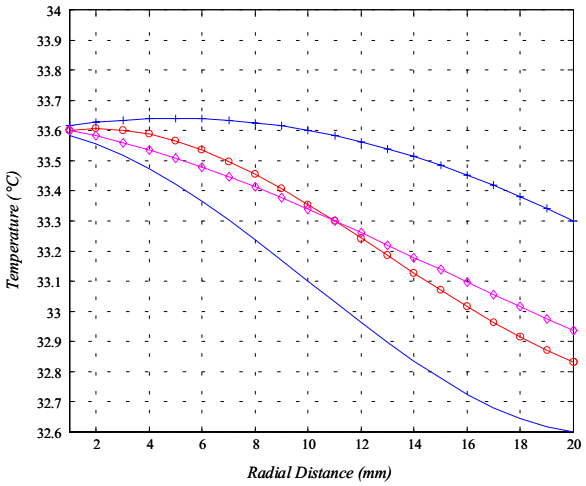

Fig. 5. Temperature profile of unidirectional model and

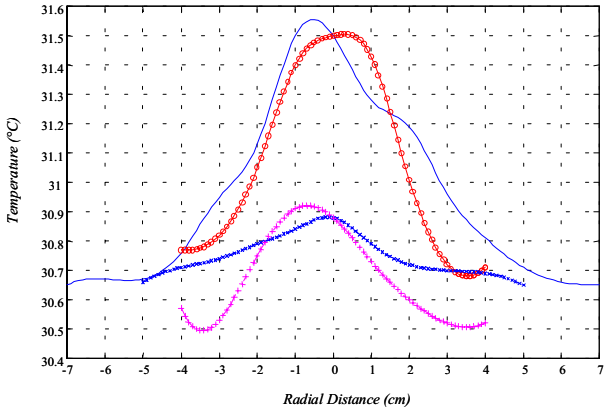

Fig. 6. Spatial resolution of mammary gland tumor imitator.
-, o : Tumor imitator with thermo-anomaly
x, + : Tumor imitator without thermo-anomaly

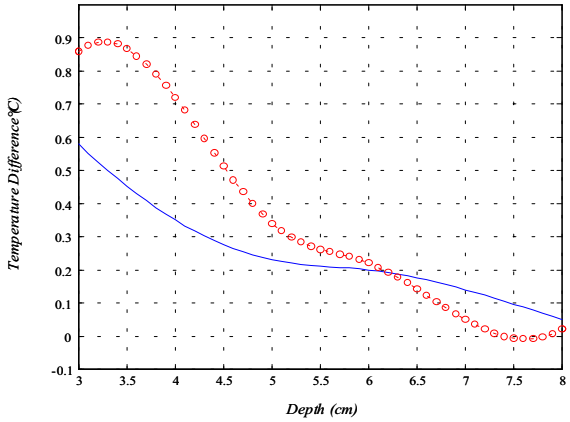

Fig. 7. The dependence of temperature difference on tumor imitator depth.

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